

# SUPERFUND DECISION ANALYSIS IN PRESENCE OF UNCERTAINTY

By Aaron A. Jennings,<sup>1</sup> Member, ASCE,  
Neel Mehta,<sup>2</sup> Student Member, ASCE, and Sumeet Mohan<sup>3</sup>

**ABSTRACT:** Environmental decision making (EDM) analysis is developing into a recognized specialty of environmental engineering. One of the major challenges of EDM is to accommodate the high levels of uncertainty that exist in many environmental problems. EDM methods based on absolute or relative, probabilistic, multiattribute utility analysis are presented. Example EDM solutions are presented for the selection of remedial action alternatives for a Superfund site using the Environmental Protection Agency's decision criteria and New York's system for quantifying decision criteria. The advantages and limitations of both are discussed. Results illustrate that the major advantages of EDM analysis are in the need to formalize the decision criteria by which a decision is made and the value judgments that are applied to weigh multiple criteria. EDM analysis can also improve decision process documentation and can sharpen the quality of debate about controversial decisions.

## INTRODUCTION

Environmental engineers are often required to help make difficult decisions. Good decision making can always be difficult. There is truth in the adage that anyone who thinks a problem is simple probably doesn't understand the problem. It is certainly possible to confuse relatively clear issues with superficial detail, misplaced emotion, and arbitrary constraints, but it is usually quite difficult to reduce sophisticated technical problems to simple, nondebatable issues.

Decision making can be particularly difficult in environmental engineering for several reasons. Consider the problem of making good decisions about hazardous wastes. Most people agree that "good" hazardous-waste management is important and that we must improve our waste-management practices. Unfortunately, that is often the extent to which there is agreement. People disagree vigorously about the nature of the threats posed by hazardous wastes and about how much priority society should place on resolving these versus the other problems of modern civilization. People also lack confidence in our ability to engineer satisfactory solutions to hazardous-waste problems. The quality of hazardous-waste management certainly matured over the last decade. Activities that were state-of-the-art a few years ago are now unacceptable. Many of the national priority list (NPL) Superfund sites were originally considered to be acceptable waste-disposal activities. We now believe that our improved technologies offer permanent solutions. Unfortunately, few of these have withstood the test of time, and we do not have a particularly good record for anticipating long-term success.

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<sup>1</sup>Prof., Dept. of Civ. Engrg., The Case School of Engrg., Case Western Reserve Univ., 10900 Euclid Ave., Cleveland, OH 44106-7201.

<sup>2</sup>Lab. Mgr., Total Source Analysis, Inc., 510 Dickson St., Wellington, OH 44090.

<sup>3</sup>Envir. Engrg. Specialist, Office of Air Quality, P.O. Box 600, Phoenix, AZ 85001-0600.

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We said much the same thing 10 years ago and have since proved ourselves wrong.

We have certainly improved hazardous-waste management over the last decade. We now have more information on the properties of hazardous materials, better waste-management technologies, and more stable regulations. However, this has not altered the fact that hazardous-waste activities are unpopular and will remain controversial for many years. As we have eliminated the most outrageous of our hazardous-waste problems (such as stacks of abandoned, leaking drums) we have also exhausted the cases where "easy" decisions can be made. Engineers now face problems that are more scientifically challenging and must be resolved in a more sophisticated technical, social, political, and legal environment. To be successful, engineers must become more sophisticated about participating in the decision-making process. Because of this, environmental decision making (EDM) is rapidly evolving as a recognized specialty of environmental engineering [see *Environmental* (1991); Guariso and Werthner (1989); *Expert* (1990)].

The goal of the present paper is to present methods of EDM analysis and to illustrate how these may be applied to controversial environmental problems such as selecting Superfund remediation technologies. The probabilistic decision alternative evaluation (P-DAE) and probabilistic decision alternative ratio evaluation (P-DARE) methods discussed are stochastic versions of multiattribute utility analysis. Both methods have been developed into microcomputer software packages capable of automating relatively efficient Monte Carlo solutions to support quantitative decision making. Although solution procedures are discussed, the goal of the present paper is to illustrate how these techniques may be applied to support environmental decision making.

## HAZARDOUS WASTE AND EDM

Decision analysis is well developed in disciplines such as business, medicine, military science, and engineering. There has been a great deal of theory developed on decision philosophy and psychology (utility theory, multiperson decision making), model design (decision tree, optimization, expert systems), model implementation (linear programming, dynamic programming, artificial intelligence), and the impact of uncertainty on decision processes (fuzzy decision making). All of this can be and probably has been applied to EDM.

In the area of hazardous wastes and particularly with respect to the Superfund program, it is more difficult to identify EDM applications. There has certainly been a large number of modeling applications, but most tend to concentrate on the prediction of a state variable such as contamination concentrations rather than on participation in the decision-making process.

The Environmental Protection Agency's (EPA's) hazard ranking system (HRS) is a model designed to yield judgmental information. Since July 1982, EPA has used the HRS model to determine which hazardous-waste sites should be listed on the NPL and thus be eligible for Superfund funding. The original model was based on a composite score  $S$

$$S = S_M + S_{FE} + S_{DC} \quad (1)$$

made up of an  $S_M$  score for the potential to do human or environmental damage by migration; an  $S_{FE}$  score for potential explosion/fire hazards; and an  $S_{DC}$  score for the direct-contact hazard (Wu and Hilger 1984). An  $S_M$

cutoff score of 28.5 was used to prepare the list of 418 NPL sites proposed in December of 1982 (Wells and Caldwell 1990). However, the HRS is not an EDM model because its results were used to decide NPL listings. The HRS is an EDM model because it actually participated in the decision-making process. The HRS scores are composite numbers computed from subfactor scores and factor weight multipliers that represent (make) value judgments about the relative importance of the decision factors. When it was proposed, the HRS model was the object of significant criticism (Frost 1982; Harris et al. 1984; Wu and Hilger 1984). Much of this related directly to the model's implied value judgments. In the Superfund Amendments and Reauthorization Act of 1986 (SARA) Congress instructed EPA to revise the HRS model (Call and Merkhofer 1988; Wells and Caldwell 1990; Cline and McLaughlin 1990), but it maintains its function of determining NPL listing.

The Department of Energy (DOE) has also experimented with EDM models to support its remedial action obligations. DOE's multimedia environmental pollutant assessment system (MEPAS) was developed to assess endangerment problems at DOE sites (Hartz and Whelan 1988; Droppo and Hopes 1990). DOE's remedial action assessment system (RAAS) was designed to provide guidance in remediation feasibility studies (Hartz and Whelan 1988). The HAZRISK system was also developed to assist in cost estimating, contingency setting, and scheduling for hazardous-waste cleanup projects (Hudson and Shangraw 1990). However, DOE's program optimization system (POS) model is probably the best example of EDM. The POS system is based on a multiattribute utility  $U$

$$U = W_{hs}U_{hs}(X_{hs}) + W_{rr}U_{rr}(X_{rr}) + W_{pc}U_{pc}(X_{pc}) - W_{rc}C_{rc} - W_{fc}C_{fc} \quad (2)$$

and was designed to optimize DOE spending on environmental restoration (Merkhofer et al. 1988). The  $X$ 's in (2) are performance scores for health and safety considerations  $hs$ , regulatory responsiveness  $rr$ , and public concern  $pc$ . The  $U$ 's are functions defining the utility of  $X$  scores, and the  $C$ 's are remaining  $rc$  and future  $fc$  costs. The  $W$ 's are weights that define the importance placed on each decision factor. The POS system has been used in DOE's budget planning and in the regional allocation of site remediation funds.

The Department of Defense (DOD) has also developed EDM models for its remedial programs. The defense priority model (DPM) is designed to estimate the relative risk to human health and the environment from DOD hazardous-waste sites (*Expert* 1990). The system evolved from the hazard assessment risk model (HARM) originally developed for the U.S. Air Force, but has since been adopted by all the armed services (Hushon 1990). The DPM considers the hazards of source materials and pathways to human and environmental receptors. Weighted subscores are combined into a total site score. Presumably, this score is used to prioritize DOD remedial actions.

Several other EDM models have been developed. FLEX (flexible liner expert) is designed to evaluate the chemical compatibility of liners used at hazardous-waste sites (Rossman and Siller 1987). HEPRM (human exposure potential ranking model) has been used to rank sites and allocate funds in New York State's Superfund program (Smith et al. 1987). DRASTIC (Allert et al. 1987) has been found useful for preliminary hazardous-waste site assessment (Mustalish and Costanzo 1991). CORA (cost of remedial action) is designed to assist in cost analysis of remedial actions (Chen and

Crenca 1990). PAST (potential ARAR's selection tool) is designed to help decision makers identify applicable or relevant and appropriate requirements (ARARs) that affect cleanup requirements (Greathouse and Clements 1991).

One of the common properties of all of these EDM models is that they are quite specialized. Specialization can be desirable, but there are also generalizations that can be made about the structure of nearly all decision-making problems. The techniques presented here are designed to address more generic decision problems. Specialization is required to develop the input data, but does not alter the structure of the decision mathematics.

## QUANTITATIVE SUPPORT OF EDM

There are five essential requirements for the decision analysis discussed. The first two require the structure of the problem to be deterministic. There must be a known set of  $N > 1$  decision variables from which to select. One of these may be a passive option such as "do nothing," but reasonable decisions can only be made about alternatives that are known. Decision problems are indeterminate if one of the decision variables is unknown because the unknown variable could be infinitely better or infinitely worse than any of the known alternatives. There must also be a set of  $M \geq 1$  criteria to be used in making the decision. Again, a decision problem is indeterminate if any of the decision criteria are unknown. Multiple decision criteria are common, but not essential.

The third requirement is for a method of evaluating decision alternatives relative to decision criteria (i.e., a measure of utility or disutility). For example, if cost is a criterion, then a method must exist to quantify the absolute or relative cost of decision variables. If risk is a criterion, then a method must exist to quantify risk. Decision problems are indeterminate if the criteria cannot be quantified, but the requirements of quantification are quite unrestrictive. Quantifications must be cardinal in nature, finite, and real, but may be on relative or absolute scales. Results may be either deterministic or probabilistic. There is also no requirement for homogeneous scales. It is quite acceptable to combine costs in dollars with impacts based on cancer risk threshold (CRT) concentrations. The quality of quantification procedures affects the quality of the resulting decision, but a good decision process should function with the best available level of information even if "best" is not very good.

The fourth requirement is for a method of specifying the relative importance of each decision criterion. Again, a multicriteria decision problem is indeterminate if the relative importance of criteria cannot be determined (unless one is superior by all criteria). The methods presented here require that either deterministic or probabilistic weights be assigned to each decision criterion. Weights embody the value judgments imposed on the decision process. A great deal of literature may be found on strategies for determining appropriate weights (Eckenrode 1965; Gum et al. 1976; Klee 1980; Knox et al. 1986).

The final requirement is for a solution procedure for the implied decision problem. Ultimately, this should determine if there is a preferable decision variable and how preferable the variable actually is. For most realistic problems, these answers must be stated as probabilities.

One method of decision analysis is P-DAE. Assume that each decision variable is evaluated on a dimensionally heterogeneous but deterministic

scale and that the resulting values are entered in an  $N \times M$  matrix  $\mathbf{U}$  with elements  $U_{nm}$

$$U_{nm} = U_m(\mathbf{X}_n) \quad (3)$$

where  $U_m$  = the utility function for the  $m$ th decision criterion; and  $\mathbf{X}_n$  = the set of variables describing the  $n$ th decision alternative. Also, assume that deterministic weights are specified for each of the  $M$  criteria and are entered in vector  $\mathbf{W}$  with elements  $W_m$ . The  $W_m$  values must respect the constraints of (4) and (5)

$$0.0 \leq W_m \leq 1.0; \quad \forall m = 1, M \quad (4)$$

$$\sum_{m=1}^M W_m = 1.0 \quad (5)$$

It would be convenient if the multiplication  $\mathbf{UW}$  would yield a rating vector  $\mathbf{R}$  whose elements  $R_n$  define the preferability of decision variables. This cannot be done directly for several reasons. The magnitude of the number in the columns of  $\mathbf{U}$  may vary by several orders of magnitude. One column may hold costs in millions of dollars. Another may hold CRT values in micrograms per liter. The  $\mathbf{UW}$  multiplication would allow the magnitude of large-value scales to overwhelm the importance of other considerations. Multiplication would also be inappropriate if the units are heterogeneous or if the scales mix utility and disutility.

The utility/disutility problem must be resolved by definition. All scales must be defined so that increasing numbers indicate either utility or disutility. The problems of number magnitude and dimensional nonhomogeneity may then be solved by normalizing each column of  $\mathbf{U}$  to yield  $\mathbf{V}$

$$\left\{ V_{nm} = \frac{U_{nm}}{\sum_{n=1}^N U_{nm}}; \quad \forall n = 1, N \right\}; \quad \forall m = 1, M \quad (6)$$

Eq. (7) will then yield a cardinal scale rating vector  $\mathbf{R}$  that satisfies the essential requirements of decision making. The numerically superior alternative will either be at the top or bottom of  $\mathbf{R}$  scale depending on whether the  $U_m$  functions define utility or disutility

$$\mathbf{VW} = \mathbf{R}; \quad 0.0 \leq R_n \leq 1.0; \quad \forall n = 1, N \quad (7)$$

Eq. (7) yields the solution when all of the information is deterministic. Unfortunately, information is seldom deterministic in realistic environmental problems. Generally there are several levels of information quality and sufficient debatability to question nearly all data.

There are several ways of accommodating uncertainty in decision analysis [see *Multiperson* (1990); Zimmermann (1987)]. Jennings and Suresh (1986) present a method for bounding the elements of  $\mathbf{R}$  based on bounds about the elements of  $\mathbf{U}$  or  $\mathbf{W}$ . Bounded-set uncertainty leads to analytical solutions for the bounds of the elements of  $\mathbf{R}$ . However, although the bounds are infallible, they are also quite conservative and can lead to high degrees of nonuniqueness (Jennings 1988). When a similar analysis was applied to the results of 12 EPA experts who evaluated 20 hazardous-waste sites, the results implied that 19 of the 20 sites were indistinguishable (Call and Merkhofer 1988).

For most problems, the probability of  $R_n$  values actually falling near their

theoretical extremes is very small. When uncertainty is quantified with finite probability density functions (PDFs), the apparent nonuniqueness of many problems can be reduced (Jennings 1988).

In the solution technique discussed here, it is assumed that the elements of  $\mathbf{U}$  and  $\mathbf{W}$  are uncertain, but may be described by finite PDFs. For example, uncertainty about a questionable CRT value might be expressed by representing the CRT as a random variable uniformly distributed over  $\pm 50\%$  of its apparent value. Nonfinite PDFs such as the Gaussian may be applied by restricting the domain of the random variable. Given that a different PDF could be specified for each element of  $\mathbf{U}$  or  $\mathbf{W}$ , the resulting  $\mathbf{R}$  values will be probabilistic and must be evaluated numerically by techniques such as Monte Carlo simulation (Kalos and Witlock 1986).

Let  $\mathbf{V}_q$  be a random Monte Carlo realization of  $\mathbf{V}$  and  $\mathbf{W}_q$  be a random realization of  $\mathbf{W}$  subject to the constraints of (4) and (5). The  $q$ th realization of  $\mathbf{R}$  may be computed as follows:

$$\mathbf{V}_q \mathbf{W}_q = \mathbf{R}_q \quad (8)$$

This calculation must be repeated numerous ( $Q$ ) times to assemble the probabilistic responses of the elements of  $\mathbf{R}$ . Given sufficiently large  $Q$ , one may develop histograms for each of the elements of  $\mathbf{R}$ , determine the probabilities of the relative rankings, or evaluate measures on solution accuracy and sensitivity. "Sufficiently large"  $Q$  governs the accuracy of the solution and may be determined by comparing the results of several independent simulations for convergence and stability. Sensitivity is a measure of how sensitive the solution is to individual probabilistic terms.

Solution sensitivity may be evaluated with measures such as the rank probability matrix  $\mathbf{A}$ , which has elements  $A_{nn'}$  that approximate the probability of the  $n$ th decision variable being ranked as  $n'$ th out of the  $N$  possible rankings. In utility formulations, the probabilities are computed as follows:

$$A_{nn'} = \left[ \frac{\text{number of times } R_n \geq (N - n' + 1)\mathbf{R} \text{ values}}{\text{number of Monte Carlo realizations}}; \quad \forall n' = 1, N \right];$$

$$\forall n = 1, N \quad (9)$$

In problems defined on disutility, the direction of the  $\geq$  condition must be reversed. One may also evaluate sensitivity matrices to analyze the impact of  $\mathbf{U}$  or  $\mathbf{W}$  elements on  $\mathbf{R}$ , and thus determine what additional information would be most valuable in improving the quality of the solution.

Details of the numerical solution of probabilistic decision-making problems are interesting, but the goal of the present paper is to illustrate the process rather than to focus on solution details. Let it suffice to say that software is available to implement all required calculations, and to support uncertainty defined by any of a large number of discrete or continuous common PDFs (Mohan 1991).

Eq. (7) requires independent decision criteria utility quantifications  $U_{nm}$ . Although many environmental decision criteria can be quantified on independent scales, it is sometimes more convenient to use relative comparisons. A deterministic process based on relative evaluations was introduced by Klee (1971). The potential advantages of relative evaluations have been discussed by Klee (1971), Jennings and Sholar (1984), Jennings and Suresh (1986), and Jennings et al. (1991). For emotionally sensitive criterion such as cancer risk, relative evaluations tend to help reduce unrealistic conser-

vatism. However, their greatest value is probably achieved when absolute scales are difficult to define. Taste or smell, for example, are quite difficult to quantify on absolute scales, but are easy to evaluate by relational comparison.

For ratio-based P-DARE solutions, decision alternatives are evaluated in pairs for each decision criterion, and a matrix  $U'$  is generated from the  $(N - 1)M$  pairwise comparisons. Matrix  $U'$  elements could be computed from absolute-scale values, but when complete absolute-scale information is available there is no need for the ratio evaluation procedure. Rather, the values of the ratios  $U'_{nm}$  are developed directly. The definition of (9) may then be used to reconstitute the relational information on an equivalent nondimensional absolute scale that is a satisfactory equivalent of the  $U$  matrix

$$U'_{nm} = \frac{U_m(X_n)}{U_m(X_{n+1})} \quad (10)$$

$$U'_{Nm} = 1.0; \quad \forall m = 1, M \quad (11)$$

$$\left[ U_{nm} = \prod_{k=n}^N U'_{nm}; \quad \forall n = 1, N \right]; \quad \forall m = 1, M \quad (12)$$

If the elements of  $U'$  are deterministic, the solution is given by (7). If the elements of  $U'$  are probabilistic, the solution must be developed numerically by (8). In the latter case, elements of  $U'_{nm}$  must be sampled and constructed into  $U_{nm}$  values for each Monte Carlo realization.

Because the calculations of (12) are done independently for each of the  $M$  columns of  $U'$ , and because these calculations yield values equivalent to  $U$  column entries, relative and absolute scales may be combined within a single decision-making problem.

## PROCESS OF SUPERFUND REMEDIATION

The Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) allows the federal government to respond directly whenever a waste-disposal site presents a significant threat of a hazardous-substance release that would pose an immediate and substantial danger to public health or the environment. CERCLA Section 105 required EPA to revise the national contingency plan (NCP) originally developed under the Clean Water Act (P.L. 95-217). The revised NCP was to contain at least 400 of the highest priority sites in the United States and provide an initial ranking of their severity. EPA published a list of the 115 highest priority sites in October of 1981, listing 24 as potentially more dangerous than the well-known Love Canal site. The NPL was expanded to 418 sites in December of 1982, to 786 by October, 1984, and continues to evolve. It currently contains over 1,200 sites, including more than 100 Federal facilities.

With time and the enactment of the SARA, the procedure for listing sites on the NPL has been refined, and a process for their remediation has evolved. Once listed and prioritized, remediation strategies are evaluated in the remedial investigation and feasibility studies (RI/FS) process. These parallel studies are intended to determine the nature and extent of threats posed by the site and to identify feasible remedial actions that could reduce these threats. Once the RI/FS process is complete, an EPA decision maker

must decide on the method of remediation. This decision is documented in a formal record of decision (ROD). Once the ROD has been finalized, the detailed remedial design (RD) is executed. This is followed by the actual remedial action (RA) and by legal actions to recover compensation from potentially responsible parties (PRPs) who are not already participating in the remediation.

This process involves several important decisions, but the most critical is made when the RI/FS information is used to select the remediation that will actually be implemented. The example presented here illustrates how EDM could enrich this act of environmental decision making.

## **SUPERFUND REMEDIATION DECISION CRITERIA**

Because EPA must respond to several legislative mandates involving hazardous waste site remediation, it has established guidance on how remedial actions should be selected. EPA has established three sets of decision criteria that must be applied. Threshold criteria must be applied to all proposed remedial actions to determine if they satisfy minimum levels of acceptability. Primary balancing criteria must then be applied to determine the most desirable approach. The selected remediation must also withstand the test of modifying criteria based on state and community acceptance. These criteria are discussed in more detail in the following section.

There is certainly no universal agreement about EPA's decision criteria. Although criteria such as cost are reasonably well defined, others such as implementability seem vague and difficult to quantify. Also, criterion such as reduction of toxicity, mobility, or volume that seem to be quite specific become very debatable when applied to the wide variety of NPL sites.

EPA also omitted essential elements of a well-defined decision problem. To apply a decision criterion, one must know the criterion, how it is quantified, and how much importance it should be given relative to other criteria. Although EPA (*Federal* 1988) defined the criteria, it did not specify how they should be quantified or how much weight each should be given. Subsequent guidance has been developed on quantifying some criteria, but criteria weights have not been published. Apparently it is EPA's policy that the weights applied to remediation decisions should be site-specific values determined as part of the RI/FS and decision-analysis process.

EPA's reluctance to publish decision criteria weights is understandable. It is easy to conceive of cases where fixed weights could lead to poor decisions. One would not want to select an otherwise outstanding alternative if it were not implementable or to select a poor solution simply because it was very inexpensive. However, the lack of guidance on appropriate weights has led to controversial decisions that have been viewed as arbitrary and inconsistent. One can certainly argue that, if the decision maker can define the weights any way desired, then the decision maker could probably justify selecting any of the remediation alternatives. If near-zero weights were assigned to threshold criteria, the remediation selected might not even be minimally acceptable. This criticism has led some states to develop additional guidance on how EPA's criteria should be applied.

In a 1991 survey (Mehta 1992), one-third of the states responding indicated that, generally, in response to legislative mandate, EPA's decision criteria were expanded either by adding criteria, specifying quantification procedures, or providing guidance on criterion weights. Of the states responding to this survey, New York has probably gone the farthest in structuring the remediation alternative selection process.

## NEW YORK'S DECISION CRITERIA REFINEMENT

In the example presented here, the New York refinement (“Technical” 1990) of EPA’s decision criteria is applied. This system was selected to illustrate both the advantages and potential difficulties of “refining” the implementation of EPA’s decision criteria. The New York system was originally intended for application to federal Superfund, state Superfund, and PRP sites (“Technical” 1990). However, it is our understanding that EPA did not approve of the system and it is not formally applied to federal Superfund.

The New York system is based on a two-tiered point-scoring procedure applied to remedial alternatives. A preliminary screening is conducted to determine if potential remedial actions are able to meet remediation objectives, are sufficiently implementable, and are sufficiently effective in the short and long term. This screening is conducted using short-term/long-term effectiveness and implementability scoring systems. Any remedial action scoring less than 10 on the first, or less than 8 on the second may be eliminated from consideration. Remedial actions that pass the preliminary screening are subjected to more detailed analysis based on EPA’s threshold and primary balancing criteria. The system also specifies the weight given to each decision criterion:

- Overall protection of human health and environment (20 points;  $W = 0.20$ ). A remedial action is “protective” if it adequately eliminates, reduces, or controls all current and future risks posed through each possible pathway. If hazardous wastes remain at the site, exposures must be acceptable. Implementation may not result in unacceptable short-term risks.
- Compliance with ARARs (10 points;  $W = 0.10$ ). Remedial actions should satisfy all ARARs or there must be a good rationale for waiving these requirements.
- Long-term effectiveness and permanence (15 points;  $W = 0.15$ ). Remedial actions must ensure long-term protection of human health and the environment. Analysis of long-term impacts must focus on risks that remain after completion of the remedial action.
- Reduction of toxicity, mobility, or volume (15 points;  $W = 0.15$ ). This criterion specifically addresses the statutory preference for “treatment” remediations by ensuring that remediations’ potential for reducing toxicity, mobility, or volume be analyzed.
- Short-term effectiveness (10 points;  $W = 0.10$ ). Short-term impacts on the neighboring community, site workers, and surrounding environment must be considered. Cross-media impacts and project duration must also be considered.
- Implementability (15 points;  $W = 0.15$ ). The technical and administrative feasibility of the remediation project, and the availability of essential goods and services must be considered.
- Cost (absolute dollar scale;  $W = 0.15$ ). The total project-life cost of construction, operation, and maintenance should be considered. Net present worth is used as the basis of comparison.

EPA’s modifying criteria of state acceptability and community acceptability are not used in New York’s procedure. Fig. 1 presents an example

REDUCTION OF TOXICITY, MOBILITY OR VOLUME  
(Relative Weight = 15)

Analysis Factor	Basis for Evaluation During Detailed Analysis	Score	
1. Volume of hazardous waste reduced (reduction in volume or toxicity) If Factor 1 is not applicable go to Factor 2.	i) Quantity of hazardous waste destroyed or treated Immobilization technologies do not score under Factor 1.	99-100% _____ 8	
		90-99% _____ 7	
		80-90% _____ 6	
		60-80% _____ 4	
		40-60% _____ 2	
	ii) Are there untreated or concentrated hazardous waste produced as a result of (i.)? If answer is no, go to Factor 2.	Yes _____ 0	
		No _____ 2	
	Subtotal (maximum = 10) If subtotal = 10, go to Factor 3	iii) After remediation, how is the untreated, residual hazardous waste material disposed?	Off-site land disposal _____ 0
			On-site land disposal _____ 1
			Off-site destruction or treatment _____ 2
2. Reduction in mobility of hazardous waste.  If Factor 2 is not applicable go to Factor 3	i) Quality of Available Wastes Immobilized after Destruction/ Treatment	90-100% _____ 2	
		60-90% _____ 1	
		< 60% _____ 0	
	ii) Method of Immobilization - Reduced mobility by containment - Reduced mobility by alternative treatment technology	_____ 0	
		_____ 3	
Subtotal (maximum = 5)			
3. Irreversibility of the destruction or treatment or immobilization of hazardous waste	Completely irreversible.	_____ 5	
	Irreversible for most of the hazardous waste constituents.	_____ 3	
	Irreversible for some of the hazardous waste constituents.	_____ 2	
	Reversible for most of the hazardous waste constituents.	_____ 0	
Subtotal (maximum = 5)			
Total (maximum = 15)			

**FIG. 1. Example New York Work Sheet for Evaluating Decision Criteria**

work sheet for quantifying reduction of toxicity, mobility, or volume. Detailed work sheets for all criteria may be found in "Technical" (1990). These are the equivalent of  $U_m(X_n)$  functions of (3), and yield the required  $U_{nm}$  values.

For the purpose of this illustration, (and only for this purpose) the New York system is applied to the Hagen Farm Superfund site. Readers should understand that this is done to illustrate the potential of EDM analysis, not to debate the merits of the New York system or EPA's decision about Hagen Farm remediation.

### HAGEN FARM SITE DESCRIPTION

The Hagen Farm site is located in Dane County, approximately 1 mile east of the city of Stoughton, Wisconsin. The 4 ha (10 acre) site is in a rural setting dominated by agriculture or sand and gravel mining. The site is in an area of flat to gently rolling topography. Surface-water drainage in the

area is poorly developed, apparently due to the high permeability of the near-surface soils. The site is located in glacial outwash deposits underlain by sandstones and dolomites at depths of 15–25 m. The current site topography is the result of sand and gravel mining, waste-disposal activities, and initial Superfund remedial actions.

The site was operated as a sand and gravel pit prior to the late 1950s. The gravel pit was then used for waste disposal from the late 1950s to the mid-1960s. It is believed that, in addition to more conventional municipal wastes, waste solvents (acetone, butyl acetate, 1-2-dichloroethylene, tetrahydrofuran), solid vinyl, and organic sludges containing methylethylketone, xylenes, and toluene were disposed of at the site.

In 1980, in response to public complaints, the Wisconsin Department of Natural Resources began ground-water sampling in nearby private wells, which were found to be contaminated. In 1983, the State of Wisconsin brought an enforcement action against the site operators using the strategy of “abatement of a public nuisance.” The site was proposed for inclusion on the NPL in September of 1985 and listed on the NPL in July of 1987. The RI/FS process was begun in July of 1988. During this process, the site was divided into two operable units made up of (1) The waste materials remaining in the underground disposal areas; and (2) the contaminants in the ground-water plume around the site. The decision analysis presented here focuses on the remediation of the first operable unit. The RI/FS and proposed remediation plan for operable unit 1 were released in July of 1990. The ROD was signed on Sept. 17, 1990. Although less than rapid, this 10-year schedule is reasonably typical of Superfund sites remediated during the 1980s. Of the 71 sites added to the NPL in February of 1990, 31 sites (about 44%) took more than 10 years to go from discovery to final listing (Kruger and Hanson 1990).

The remedial investigation of operable unit 1 indicated that approximately 52,000 m<sup>3</sup> (68,000 yd<sup>3</sup>) of waste were buried over a 2.5 ha (6 acre) area to depths ranging from 0.6 to 5 m. The bottom of the waste was apparently 3–4.5 m above the seasonal high water table. The greatest risk at the site was judged to be from ground-water contamination. A list of remedial technologies was identified to address this risk. These technologies were then screened based on cost, implementability, effectiveness, site characteristics and contaminant characteristics. The following remedial action alternatives survived the initial screening:

1. No action. Included as required by the NCP.
2. Capping. All wastes would be consolidated into one area. The site would be graded to deflect surface runoff. A 2.2 ha (5.5 acre) impermeable cap would be placed to prevent new infiltration and minimize leachate production (time estimate: 7 months; cost estimate: \$2,888,000).
3. In-situ vapor extraction and capping. Prior to capping, wastes and subsoils would be treated by vapor extraction. Extracted gases would be treated using carbon adsorption and then discharged to the atmosphere (time estimate: 5 years; cost estimate: \$3,299,000).
4. Consolidation, biological treatment, vapor extraction, and capping. Wastes would be consolidated into a treatment/disposal cell with a high-permeability cover to allow infiltration. Leachates thus produced would be recirculated to promote biological activity. Nutrients and microorganisms would be added to promote biological activity. Excess leachate would be treated and discharged to local surface waters. When treatment was com-

plete the cell would be capped. Contaminated soils left behind after waste excavation would be treated by in-situ vapor extraction (time estimate: 10 years; cost estimate: \$14,129,000).

5. Waste excavation, on-site incineration, vapor extraction, and capping. Wastes would be excavated and incinerated on-site. The ash would be disposed of on-site in a consolidated disposal cell. Contaminated soils left after waste excavation would be treated by in-situ vapor extraction (time estimate: 5 years; cost estimate: \$59,858,000).

The EPA was then faced with the problem of selecting the alternative to be applied. In this example, we illustrate how EDM analysis could be applied in this decision-making process.

### HAGEN FARM EDM ANALYSIS

To examine preferability, the New York evaluation system was applied to the Hagen Farm remedial action alternatives. The resulting criteria scores are listed in Table 1. Ranges were considered for the scores of the first six criteria because of uncertainty in assigning factor subscores. The bounds of the scoring system were also considered to be uncertain. The cost ranges were computed as  $\pm 10\%$  of the deterministic ROD estimates. The  $\pm 10\%$  value was selected based on recent reports indicating that construction costs were generally within 5% of the ROD estimates for "routine" projects and within 20% for nonroutine projects completed in the 1980s (Richardson et al. 1990; Schroeder 1990). Variations of as much as  $-90\%$  to  $+170\%$  occurred, but much of this can probably be attributed to changes in performance requirements over this same period. Although a higher degree of variability could be justified, we assumed that the Superfund experiences of the last decade, automated cost-estimating systems such as CORA (Chen and Crenca 1990) and documents such as DOE's *Cost Estimating Handbook for Environmental Restorations* (Hudson and Shangraw 1990) will help improve future remedial-action cost estimates.

**TABLE 1. New York Point Evaluation System Score Ranges<sup>a</sup> for Hagen Farm Site Remedial Action Alternatives**

Decision variables <sup>b</sup> (1)	EPA Decision Criterion						
	DC <sub>1</sub> (2)	DC <sub>2</sub> (3)	DC <sub>3</sub> (4)	DC <sub>4</sub> (5)	DC <sub>5</sub> (6)	DC <sub>6</sub> (7)	DC <sub>7</sub> <sup>c</sup> (dollars) (8)
1	1-3	1-2	4-6	2-4	4-6	10-12	500,000
2	9-11	5-7	13-15	6-8	8-10	8-10	2,888,000
3	6-8	6-8	14-16	13-15	7-9	10-12	3,299,000
4	7-9	3-5	16-18	15-17	6-8	11-13	14,129,000
5	9-11	5-7	12-14	13-15	7-9	10-12	59,858,000

Note: Deterministic criteria weights of the New York system were as follows: DC<sub>1</sub> = 0.20; DC<sub>2</sub> = 0.10; DC<sub>3</sub> = 0.15; DC<sub>4</sub> = 0.15; DC<sub>5</sub> = 0.10; DC<sub>6</sub> = 0.15; and DC<sub>7</sub> = 0.15.

<sup>a</sup>Range of numbers bounding the uncertainty of applying the New York system to the Hagen Farm site.

<sup>b</sup>Corresponding to remediation alternatives 1-5.

<sup>c</sup>Estimated 30-year present worth cost of the remedial action alternative.

Fig. 2 presents histograms for the probabilistic ratings of Hagen Farm's five remediation alternatives computed from 50,000 Monte Carlo realizations of (8). Uncertainty was simulated as uniformly distributed over the value ranges of Table 1. The deterministic weights of the New York system were applied. Because large numbers imply higher preferability, vapor extraction appears to be the most preferable remediation strategy. This would probably constitute the superior choice. The rating histogram for vapor extraction has been highlighted on Fig. 2. This choice is not certain because, as the histograms illustrate, there is some probability that any of the five decision alternatives could be the superior choice. These probabilities, computed from (9), are illustrated in Fig. 3. Note that vapor extraction has the

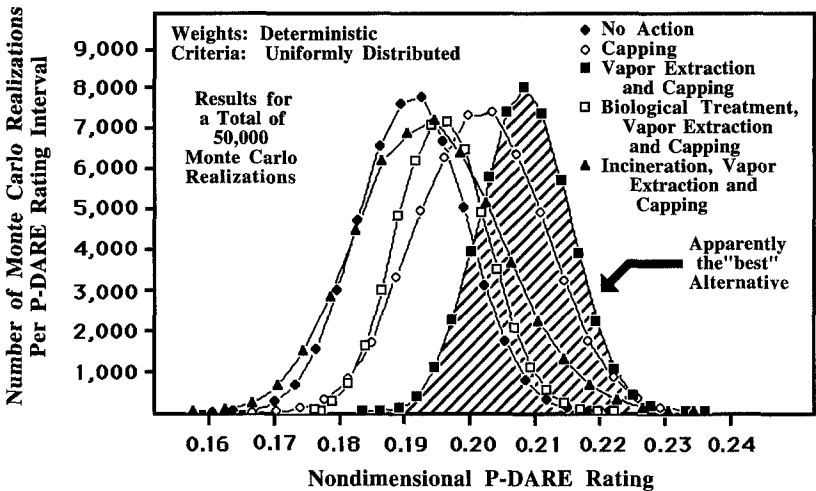


FIG. 2. Histograms Based on Deterministic Criteria Weights and Uniformly Distributed Uncertainty about New York System Rating Scores

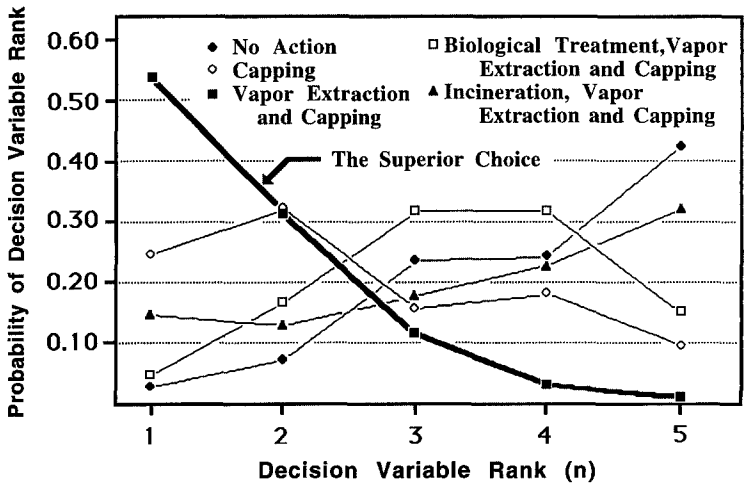


FIG. 3. Rank Probabilities of Hagen Farm Site Remedial Action Alternatives

highest probability of being the best choice and the lowest probability of being the worst choice. Reason would suggest that it is the best solution.

Figs. 4 and 5 illustrate the impact of alternative problem definitions. Fig. 4 illustrates rating histograms resulting from defining normally distributed criteria evaluations. On equivalent finite intervals a normally distributed variable is less likely to take on extreme values than a uniformly distributed one. Therefore, one should expect the resulting rating histograms to be more concentrated on the rating scale. Fig. 4 confirms this expectation, although the changes are minor. In the context of the overall decision, the

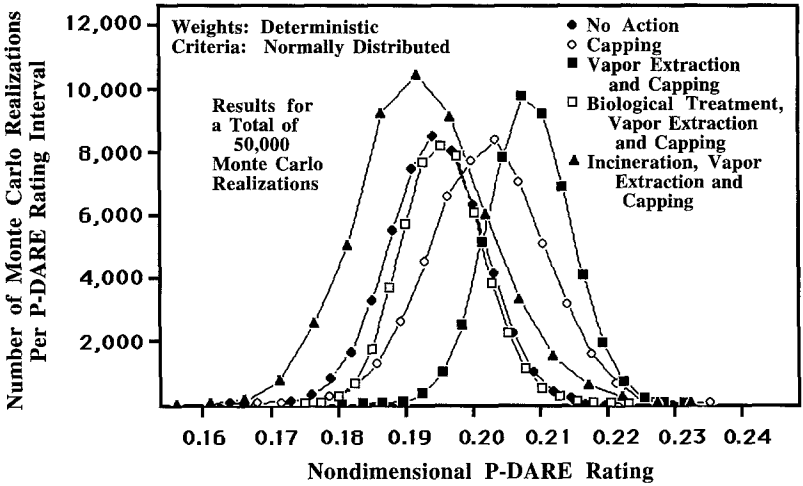


FIG. 4. Histograms Based on Deterministic Criteria Weights and Normally Distributed Uncertainty about New York System Rating Scores

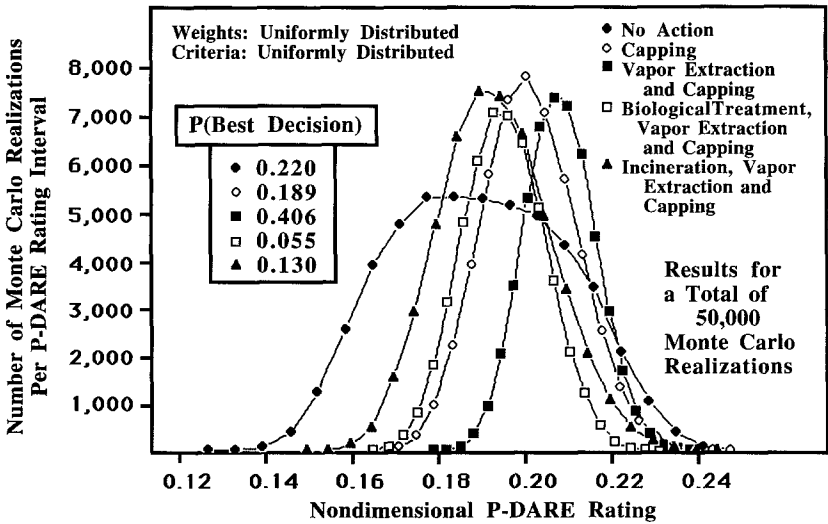


FIG. 5. Histograms Based on Uniformly Distributed Uncertainty about Both Criteria Weights and New York System Rating Scores

probability that vapor extraction is the best choice increases slightly, but the decision is not particularly sensitive to the PDF used to define uncertainty.

Fig. 5 illustrates rating histograms that result from specifying uncertainty about criteria evaluations and criteria weights. Weight uncertainty has a much greater impact on the solution. Note that, because of sensitivity to cost (the most variable criterion), the probability that vapor extraction is the best choice drops significantly, and the probability that no action is the superior choice increases. The probability that no action is the best choice increased from nearly 0 to 0.22 making it the next best choice. We note this not to imply that "no action" would have been a viable alternative for this site (we feel strongly that it would not have been), but to illustrate the potential sensitivity to imposed weights. The "no action" alternative is so inexpensive relative to most remediations that it can be the apparent solution under many weighting schemes.

## DISCUSSION OF EDM ANALYSIS OF SUPERFUND DECISION MAKING

The analysis presented in Figs. 2 and 3 indicates that vapor extraction is the best choice for the Hagen Farm site. Given New York's procedures for quantifying decision criteria and the New York weights, analysis indicates that vapor extraction best satisfies EPA's decision criteria. Fig. 3 illustrates that this decision is fallible, but that vapor extraction has the highest probability of being the superior choice. This probability (0.55) is significantly higher than the next best alternative. Vapor extraction is, in fact, the remediation EPA selected for the Hagen Farm site. If vapor extraction is actually the best decision, and if EPA was able to reach this decision without EDM analysis, why apply decision analysis at all?

First, how is one to know that EPA made the "correct" choice. The ROD is intended to explain EPA's decision. Any PRP for this site would probably want to look very carefully at the cost (i.e., the PRP liability) of the proposed solution. Environmental advocates might want to examine any decision such as this that allows hazardous wastes to remain at the site. Remaining wastes represent some possibility for long-term environmental degradation. Of course, EPA was supposed to consider these issues in its decision, but either party might want to know *how* these considerations were treated in the decision process.

The *how* is explained in the Hagen Farm ROD (*Record* 1990). The ROD does provide some discussion of the merits of alternatives relative to cost and long-term effectiveness. Unfortunately, one can find little explicit discussion of the importance that was given to the differential costs of the remediation alternatives or the importance given to the incremental value of more expensive alternatives. This is not to say that the EPA did not make the best decision. It is the author's opinion that it did. What is significant is that, for controversial problems such as selecting remedial action alternatives, more than opinion is necessary to justify critical decisions. One could easily disagree with EPA's decision. If, for example, cost is given a substantially higher relative weight, the "no action" alternative becomes the mathematically preferable choice. It would have been quite possible for a competent professional to select this as the best alternative by intuitively applying a different weighting scheme. It is just as possible to justify the very expensive incineration alternative if very little weight is given to cost.

We contend that the weights are the source of much of the controversy about decisions of this type. Although one can question the cost estimates

of proposed remediations, the real issue revolves around how much importance cost is given relative to other critical issues. Quantitative EDM analysis forces the decision maker to resolve and document critical components of the decision process. One might view this as exposing more than is prudent about the decision process, but this is an obligation under the Superfund program. It may subject these decisions to additional debate, but so be it. If the process helps to focus debate on valid environmental issues, the Superfund program will ultimately benefit. Good decisions will survive the process—poor decisions should be changed.

A second reason for incorporating quantitative EDM analysis is the ability to accommodate uncertainty. It is clear that the decision maker in this case did not have precise information. The cost estimates, for example, could have been in error by as much as 170% (Richardson et al. 1990). Estimates for criteria such as long-term effectiveness and permanence could be little better. This is no reason why “good” decisions cannot still be made, but it is essential for the decision maker to consider uncertainty in the decision process. It would probably be a legally flawed decision if the decision maker actually thought the numbers were precise and based the decision on this erroneous expectation. Isn't it a healthier process if the decision maker acknowledges uncertainty and bases the decision on a process that considers this factor? The “answer” must then be expressed in probabilistic terms, but this is the reality of decision making. Most people would be more comfortable with results knowing that uncertainty had been considered, than knowing the decision maker was naive about the true nature of the problem.

A third compelling advantage of EDM analysis is the ability to examine the sensitivity of the superior choice to the quality of the information. Often, EPA seeks additional data in the process of deliberating over difficult decisions. One might, for example, ask for refined cost estimates if costs seemed to be dominating the decision problem. Unfortunately, it is very difficult to intuitively identify the information that would be most valuable for enriching a decision. One may be uncomfortable about cost estimates, but cost may be unimportant relative to other factors. EDM analysis allows the decision maker to identify which information has the greatest impact on the decision. This allows the decision maker to focus on refining analysis for the most crucial issues.

## **SUMMARY AND CONCLUSIONS**

EDM is a rapidly evolving specialization. Often environmental decisions involve debatable elements of science, philosophy and law that guarantee controversy. When this is coupled with a high level of uncertainty, decision makers are faced with difficult decision problems. Quantitative decision analysis is one answer to these problems. This requires that decision alternatives, decision criteria, and “relative importance” weights be specified. This helps to focus debate on the true issues and helps all parties feel that their concerns are being considered.

In the present paper, we illustrated how probabilistic decision analysis may be applied to enrich the selection process of Superfund remedial actions. Although decision criteria were established by regulation, methods for criteria quantification and criteria weights are not fixed. The included example illustrates how the decision criteria and weights may be quantified, and how information uncertainty may be analyzed. The results are rating histograms that may be used to determine what is probably the best solution, to quantify the probability, and to identify the additional information that would be

most helpful for improving the quality of the solution. Formal application of EDM techniques would enrich the Superfund program by providing essential details in the ROD. This would allow all parties to understand (and contest if desired) how EPA selects remediations that will have a profound impact on the long-term quality of our environment.

## ACKNOWLEDGMENT

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## APPENDIX II. NOTATION

*The following symbols are used in this paper:*

- $\mathbf{A}$  = rank probability matrix;
- $A_{nn}$  = probability of  $n$ th decision variable being rated as  $n$ 'th of  $N$  decision alternatives;
- $C_{fc}$  = POS model future cost;
- $C_{rc}$  = POS model remaining cost;
- $M$  = number of decision criteria;
- $N$  = number of decision variables;
- $Q$  = number of Monte Carlo realizations;
- $\mathbf{R}$  = vector of decision alternative ratings;
- $R_n$  = rating of  $n$ th decision variable;
- $\mathbf{R}_q$  =  $q$ th realization of vector of probabilistic decision alternative ratings;
- $S$  = HRS model composite score;
- $S_{DC}$  = HRS model direct-contact potential subscore;
- $S_{FE}$  = HRS model fire/explosion potential subscore;
- $S_M$  = HRS model migration potential subscore;
- $U$  = POS model composite score;
- $\mathbf{U}$  = matrix of decision criteria utilities;
- $U_{hs}$  = POS model utility function for health and safety considerations;
- $U_m$  = utility function for  $m$ th decision criterion;
- $U_{nm}$  = utility of  $n$ th decision variable relative to  $m$ th decision criterion;
- $U'_{nm}$  = relative utility of  $n$ th decision variable relative to  $m$ th decision criterion;
- $U_{pc}$  = POS model utility function for public concern considerations;
- $U_{rr}$  = POS model utility function for regulatory responsiveness;
- $\mathbf{V}$  = normalized matrix of decision criteria utilities;
- $V_{nm}$  = normalized utility of  $n$ th decision variable relative to  $m$ th decision criterion;
- $\mathbf{V}_q$  =  $q$ th realization of normalized matrix of probabilistic decision criteria utilities;
- $\mathbf{W}$  = vector of decision criteria weights;
- $W_{fc}$  = POS model weight for future costs;
- $W_{hs}$  = POS model weight for health and safety considerations;
- $W_m$  = weight applied to  $m$ th decision criterion utility;
- $W_{pc}$  = POS model weight for public concern considerations;
- $\mathbf{W}_q$  =  $q$ th realization of vector of probabilistic decision criteria weights;
- $W_{rc}$  = POS model weight for remaining costs;
- $W_{rr}$  = POS model weight for regulatory responsiveness;
- $X_{hs}$  = POS model score for health and safety considerations;
- $X_n$  = set of state variables quantifying  $n$ th decision variable;
- $X_{pc}$  = POS model score for public concern considerations; and
- $X_{rr}$  = POS model score for regulatory responsiveness.